THE MISSISSIPPIAN LEADVILLE LIMESTONE EXPLORATION PLAY, UTAH AND COLORADO – EXPLORATION TECHNIQUES AND STUDIES FOR INDEPENDENTS

SEMI-ANNUAL TECHNICAL PROGRESS REPORT October 1, 2003 - March 31, 2004

by

Thomas C. Chidsey, Jr., Principal Investigator/Program Manager,
Craig D. Morgan, and Kevin McClure,
Utah Geological Survey

August 2004

Contract No. DE-FC26-03NT15424

Virginia Weyland, Contract Manager
U.S. Department of Energy
National Petroleum Technology Office
Williams Center Tower One
1 West 3rd Street
Tulsa, OK 74103-3519

DISCLAIMER

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Submitting Organization: Utah Geological Survey
1594 West North Temple, Suite 3110
P.O. Box 146100
Salt Lake City, Utah 84114-6100
Ph.: (801) 537-3300/Fax: (801) 537-3400

ABSTRACT

The Mississippian Leadville Limestone is a shallow, open marine, carbonate-shelf deposit. The Leadville has produced over 53 million barrels (8.4 million m^3) of oil from six fields, currently operated by independent producers, in the Paradox fold and fault belt of the Paradox Basin, Utah and Colorado. The environmentally sensitive, 7500-square-mile (19,400 km^2) area that makes up the fold and fault belt is relatively unexplored. Only independent operators continue to hunt for Leadville oil targets in the region. The overall goal of this study is to assist these independents by (1) developing and demonstrating techniques and exploration methods never tried on the Leadville, (2) targeting areas for exploration, and (3) conducting a detailed reservoir characterization study. The final results will hopefully reduce exploration costs and risk, especially in environmentally sensitive areas, and add new oil discoveries and reserves.

This report covers research activities for the first half of the first project year (October 1, 2003, through March 31, 2004). This work included (1) correlating major Paleozoic formations throughout the Paradox Basin and constructing regional stratigraphic cross sections, (2) identifying fields for detailed reservoir characterization and surface geochemical surveys, and (3) technology transfer activities.

We are correlating major Paleozoic formations throughout the Paradox Basin from the wells that penetrate the Leadville Limestone. Regional stratigraphic cross sections show thickness relationships of the Leadville and will be combined with core-derived facies descriptions. Reservoir characterization of the Leadville is not complete, and little pertinent information is publicly available. The UGS recommends conducting a case study of the Leadville reservoir at Lisbon field, Utah's largest Leadville producer. The reservoir characteristics, particularly diagenetic overprinting and history, and Leadville facies can be applied regionally to other fields and exploration trends. We also recommend that surface geochemical surveys be conducted at the abandoned Big Flat field and the actively producing Lisbon field, both located in Utah. These fields are ideal because (1) proven hydrocarbons underlie the areas, (2) access is easy, and (3) the surface geology between the two is different. Proving the success of geochemical surveys will allow independent operators to reduce exploration risks and cause less impact on environmentally sensitive areas while exploring for Leadville targets.

Project technology transfer activities consisted of publications promoting the study and creation of a project home page on the Utah Geological Survey Web site. An abstract describing the Leadville Limestone play and reservoir characteristics was accepted by the American Association of Petroleum Geologists, for presentation at the 2004 Rocky Mountain Section Meeting in Denver, Colorado.

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The Mississippian Leadville Limestone is a shallow, open marine, carbonate-shelf deposit. The Leadville has produced over 53 million barrels (8.4 million m^3) of oil from six fields in the Paradox fold and fault belt of the Paradox Basin, Utah and Colorado. These fields are currently operated by small, independent producers. The environmentally sensitive, 7500-square-mile (19,400 km^2) area that makes up the fold and fault belt is relatively unexplored. Only independent operators continue to hunt for Leadville oil targets in the region. The overall goal of this study is to assist these independents by (1) developing and demonstrating techniques and exploration methods never tried on the Leadville Limestone, (2) targeting areas for exploration, and (3) conducting a detailed reservoir characterization study. The final results will hopefully reduce exploration costs and risk especially in environmentally sensitive areas, and add new oil discoveries and reserves.

To achieve this goal and carry out the Leadville Limestone study, the Utah Geological Survey (UGS) and Eby Petrography & Consulting, Inc., have entered into a cooperative agreement with the U.S. Department of Energy (DOE), National Petroleum Technology Office, Tulsa, Oklahoma. The research is funded as part of the DOE Advanced and Key Oilfield Technologies for Independents (Area 2 – Exploration) Program. This report covers research activities for the first half of the first project year (October 1, 2003, through March 31, 2004). This work included (1) correlating major Paleozoic formations throughout the Paradox Basin and constructing regional stratigraphic cross sections, (2) identifying fields for detailed reservoir characterization and surface geochemical surveys, and (3) technology transfer activities.

We are correlating major Paleozoic formations throughout the Paradox Basin from the wells that penetrate the Leadville Limestone. Regional stratigraphic cross sections show thickness relationships of the Leadville and will be combined with core-derived facies descriptions. This will provide a significant database for determining (1) potential exploration trends, (2) regional facies, (3) seals, barriers, and baffles to fluid flow, and (4) hydrocarbon migration pathways.

Reservoir characterization of the Leadville Limestone is not complete, and little pertinent information (core descriptions, permeability data, and diagenetic analysis) is publicly available. The UGS recommends conducting a case study of the Leadville reservoir at Lisbon field, Utah's largest Leadville producer. There is a wealth of Lisbon core and other data available to the UGS. The reservoir characteristics, particularly diagenetic overprinting and history, and Leadville facies can be applied regionally to other fields and exploration trends.

Surface geochemical surveys have proved helpful to identify areas of poorly drained or by-passed oil in other basins. We recommend that surface geochemical surveys be conducted, as part of the project (Phase II), at the abandoned Big Flat field as well as at the actively producing Lisbon field, both located in Utah. These fields are ideal because (1) proven hydrocarbons underlie the areas, (2) access is easy, and (3) the surface geology between the two is different. Proving the success of geochemical surveys at Big Flat or Lisbon fields will allow independent operators to reduce risks and cause little impact on environmentally sensitive areas while exploring for Leadville targets.

Project technology transfer activities consisted of publications promoting the study and creation of a project home page on the Utah Geological Survey Web site. An abstract describing the Leadville Limestone play and reservoir characteristics was accepted by the American Association of Petroleum Geologists, for presentation at the 2004 Rocky Mountain Section Meeting in Denver, Colorado.

INTRODUCTION

Project Overview

The Mississippian Leadville Limestone has produced over 53 million barrels (8.4 million m^3) of oil from six fields in the northern Paradox Basin region, referred to as the Paradox fold and fault belt, of Utah and Colorado. All of these fields are currently operated by small, independent producers. There have been no new discoveries since the early 1960s, and only independent producers continue to explore for Leadville oil targets in the region, 85 percent of which is under the stewardship of the Federal Government. This environmentally sensitive, 7500-square-mile (19,400 km^2) area is relatively unexplored with only about 100 exploratory wells that penetrated the Leadville (less than one well per township), and thus the potential for new discoveries remains great.

The overall goals of this study are to (1) develop and demonstrate techniques and exploration methods never tried on the Leadville Limestone, (2) target areas for exploration, (3) increase deliverability from new and old Leadville fields through detailed reservoir characterization, (4) reduce exploration costs and risk especially in environmentally sensitive areas, and (5) add new oil discoveries and reserves.

The Utah Geological Survey (UGS) and Eby Petrography & Consulting, Inc., have entered into a cooperative agreement with the U.S. Department of Energy (DOE) as part of its Advanced and Key Oilfield Technologies for Independents (Area 2 – Exploration) Program. The project will be conducted in two phases, each with specific objectives and separated by a continue-stop decision point based on results as of the end of Phase I. The objective of Phase 1 is to conduct a case study of the Leadville reservoir at Lisbon field (the largest Leadville producer), San Juan County, Utah, in order understand the reservoir characteristics and facies that can be applied regionally. The first objective of Phase 2 will be to conduct a low-cost field demonstration of new exploration technologies to identify potential Leadville oil migration directions (evaluating the middle Paleozoic hydrodynamic pressure regime), and surface geochemical anomalies (using microbial, soil, gas, iodine, and trace elements), especially in environmentally sensitive areas. The second objective will be to determine regional facies (evaluating cores, geophysical well logs, outcrop and modern analogs), identify potential oil-prone areas based on shows (using low-cost epi-fluorescence techniques), and target areas for Leadville exploration.

These objectives are designed to assist the independent producers and explorers who have limited financial and personnel resources. All project maps, studies, and results will be publicly available in digital (interactive, menu-driven products on compact disc) or hard-copy format and presented to the petroleum industry through a proven technology transfer plan. The technology transfer plan includes a Technical Advisory Board composed of industry representatives operating in the Paradox Basin and a Stake Holders Board composed of representatives of state and federal government agencies, and groups with a financial interest within the study area. Project results will also be disseminated via the UGS Web site, technical workshops and seminars, field trips, technical presentations at national and regional professional meetings, convention displays, and papers in various technical or trade journals, and UGS publications.

Project Benefits and Potential Application

Exploring for the Leadville Limestone is high risk, with less than a 10 percent chance of success based on the drilling history of the region. Prospect definition requires expensive, three-dimensional (3D) seismic acquisition, often in environmentally sensitive areas. These facts make exploring difficult for independents that have limited funds available to try new, unproven techniques that might increase the chance of successfully discovering oil. We believe that one or more of the project activities will reduce the risk taken by an independent producer in looking for Leadville oil, not only in exploring but in trying new techniques. For example, the independent would not likely attempt surface geochemical surveys without first knowing they have been proven successful in the region. If we can prove geochemical surveys are an effective technique in environmentally sensitive areas, the independent will save both time and money exploring for Leadville oil.

Another problem in exploring for oil in the Leadville Limestone is the lack of published or publicly available geologic and reservoir information, such as regional facies maps, complete reservoir characterization studies, surface geochemical surveys, regional hydrodynamic pressure regime maps, and oil show data and migration interpretations. Acquiring this information or producing these studies would save cash and manpower resources which independents simply do not possess or normally have available only for drilling. The technology, maps, and studies generated from this project will help independents to identify or eliminate areas and exploration targets prior to spending significant financial resources on seismic data acquisition and environmental litigation, and therefore increase the chance of successfully finding new accumulations of Leadville oil.

These benefits may also apply to other high-risk, sparsely drilled basins or regions where there are potential shallow-marine carbonate reservoirs equivalent to the Mississippian Leadville Limestone. These areas include the Utah-Wyoming-Montana thrust belt (Madison Limestone), the Kaiparowits Basin in southern Utah (Redwall Limestone), the Basin and Range Province of Nevada and western Utah (various Mississippian and other Paleozoic units), and the Eagle Basin of Colorado (various Mississippian and other Paleozoic units).

Many mature basins have productive carbonate reservoirs of shallow-marine shelf origin. These mature basins include the Eastern Shelf of the Midland Basin, West Texas (Pennsylvanian-age reservoirs in the Strawn, Canyon, and Cisco Formations); the Permian Basin, West Texas and southeast New Mexico (Permian age Abo and other formations along the northwest shelf of the Permian Basin); and the Illinois Basin (various Silurian units). A successful demonstration in the Paradox Basin makes it very likely that the same techniques could be applied in other basins as well. In general, the average field size in these other mature basins is larger than fields in the Paradox Basin. Even though there are differences in depositional facies and structural styles between the Paradox Basin and other basins, the fundamental use of the techniques and methods is a critical commonality.

PARADOX BASIN - OVERVIEW

The Paradox Basin is located mainly in southeastern Utah and southwestern Colorado, with a small portion in northeastern Arizona and northwestern New Mexico (figure 1). The Paradox Basin is an elongate, northwest-southeast-trending, evaporitic basin that predominately developed during the Pennsylvanian. The basin can generally be divided into three areas: the Paradox fold and fault belt in the north, the Blanding sub-basin in the south-southwest, and the Aneth platform in southeasternmost Utah (figure 1). The Mississippian Leadville Limestone is one of two major oil and gas reservoirs in the Paradox Basin, the other being the Pennsylvanian Paradox Formation (figure 2). Most Leadville production is from the Paradox fold and fault belt (figure 3).

The most obvious structural features in the basin are the spectacular anticlines that extend for miles in the northwesterly trending fold and fault belt. The events that caused these and many other structural features to form began in the Proterozoic, when movement initiated on high-angle basement faults and fractures 1700 to 1600 Ma (Stevenson and Baars, 1987). During Cambrian through Mississippian time, this region, as well as most of eastern Utah, was the site of typical, thin, marine deposition on the craton while thick deposits accumulated in the miogeocline to the west (Hintze, 1993). However, major changes occurred beginning in the Pennsylvanian. A series of basins and fault-bounded uplifts developed from Utah to Oklahoma as a result of the collision of South America, Africa, and southeastern North America (Kluth and Coney, 1981; Kluth, 1986),

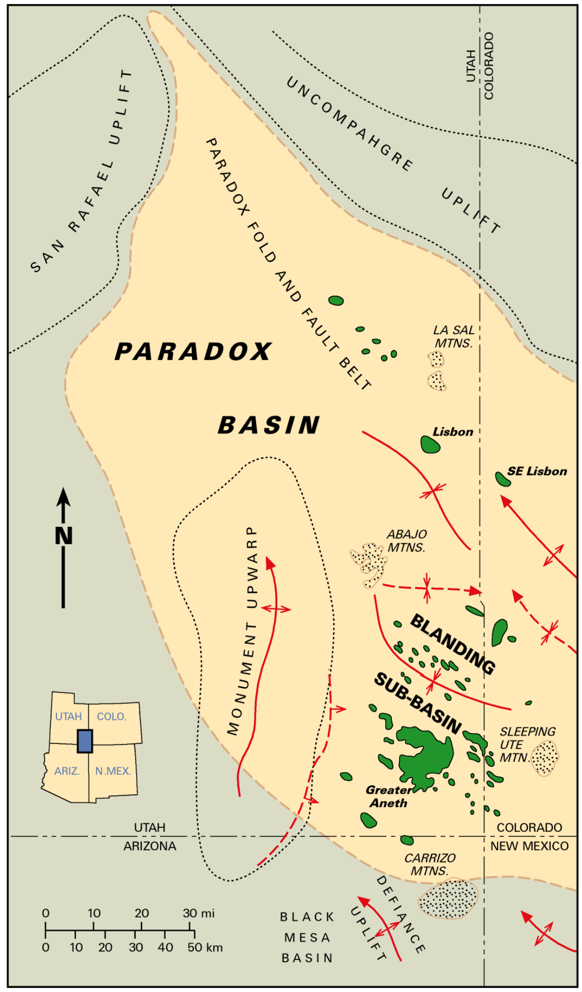


Figure 1. Oil and gas fields in the Paradox Basin of Utah and Colorado.

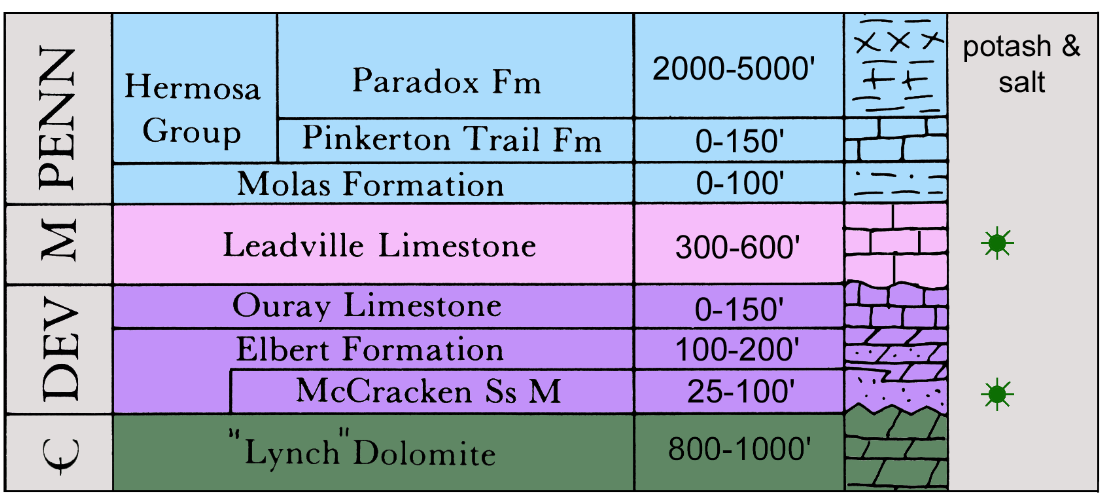


Figure 2. Stratigraphic column of a portion of the Paleozoic section determined from subsurface well data in the Paradox fold and fault belt, Grand and San Juan Counties, Utah (modified from Hintze, 1993).

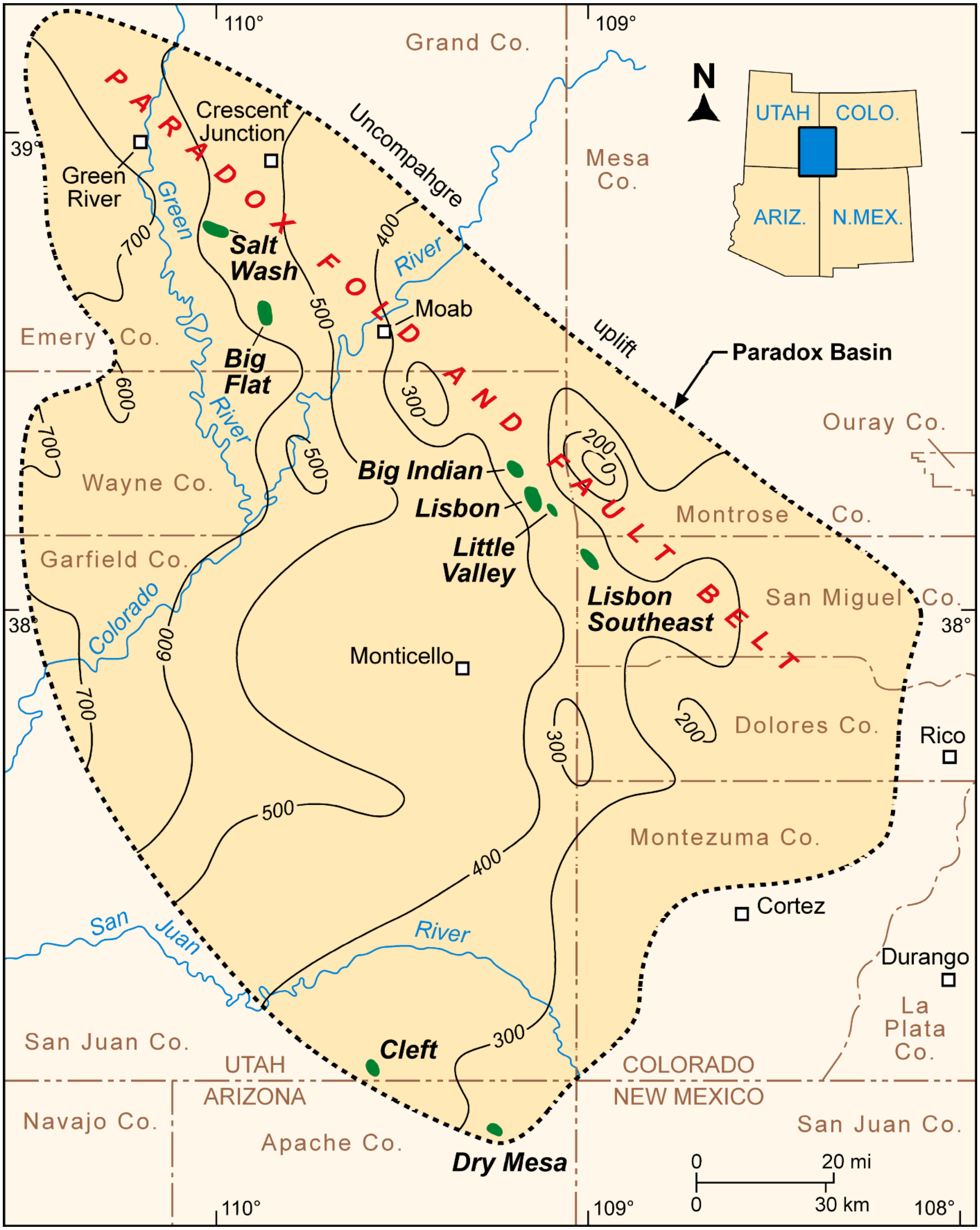


Figure 3. Location of reservoirs that produce oil (green) from the Mississippian Leadville Limestone, Utah and Colorado. Thickness of the Leadville is shown; contour interval is 100 feet (modified from Parker and Roberts, 1963).

or from a smaller scale collision of a microcontinent with south-central North America (Harry and Mickus, 1998). One result of this tectonic event was the uplift of the Ancestral Rockies in the western United States. The Uncompahgre Highlands in eastern Utah and western Colorado initially formed as the westernmost range of the Ancestral Rockies during this ancient mountain-building period. The southwestern flank of the Uncompahgre Highlands (uplift) is bounded by a large, basement-involved, high-angle, reverse fault identified from seismic surveys and exploration drilling. As the highlands rose, an accompanying depression, or foreland basin, formed to the southwest – the Paradox Basin. Rapid subsidence, particularly during the Pennsylvanian and continuing into the Permian, accommodated large volumes of evaporitic and marine sediments that intertongue with non-marine arkosic material shed from the highland area to the northeast (Hintze, 1993).

The Paradox Basin is surrounded by other uplifts and basins, which formed during the Late Cretaceous-early Tertiary Laramide orogeny (figure 1). The Paradox fold and fault belt was created during the Tertiary and Quaternary by a combination of (1) reactivation of basement normal faults, (2) salt flowage, dissolution and collapse, and (3) regional uplift (Doelling, 2000).

Most oil and gas produced from the Leadville Limestone is found in basement-involved, northwest-trending structural traps with closure on both anticlines and faults (figure 4). Lisbon, Big Indian, Little Valley, and Lisbon Southeast fields (figure 3) are sharply folded anticlines that close against the Lisbon fault zone. Salt Wash and Big Flat fields (figure 3), northwest of the Lisbon area, are unfaulted, east-west- and north-south-trending anticlines, respectively.

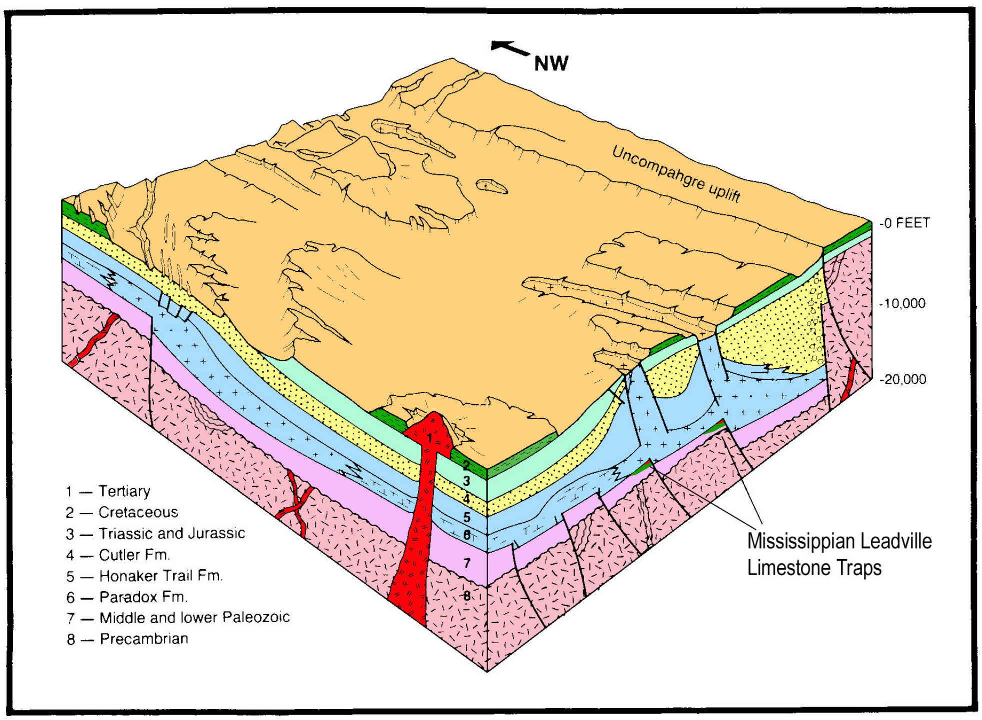


Figure 4. Schematic block diagram of the Paradox Basin displaying basement-involved structural trapping mechanisms for the Leadville Limestone fields (modified from Petroleum Information, 1984; original drawing by J.A. Fallin).

The Leadville Limestone has produced over 53 million barrels (8.4 million m^3) of oil and 826 billion cubic feet (23.4 billion m^3) of gas from the six fields in the northern Paradox Basin of Utah and Colorado (Utah Division of Oil, Gas and Mining, 2004; Colorado Oil and Gas Conservation Commission records). This 7500-mi^2 (19,400 km^2) area is relatively unexplored; only about 100 wells penetrate the Leadville (less than one well per township), thus the potential for new discoveries remains great.

REGIONAL STRATIGRAPHIC CORRELATION OF THE LEADVILLE LIMESTONE IN THE PARADOX BASIN, UTAH – RESULTS AND DISCUSSION

Data Collection and Compilation

Geophysical well logs, cores and cuttings, reservoir data, various reservoir maps, and other information from regional exploratory and field development wells are being collected by the UGS. Well locations, formation tops, production data, completion tests, basic core analysis, porosity and permeability data, and other data are being compiled and entered in a database developed by the UGS. This database, INTEGRAL, is a geologic-information database that links a diverse set of geologic data to records using MS Access™. The database is designed so that geological information, such as lithology, petrophysical analyses, or depositional environment, can be exported to software programs to produce cross sections, strip logs, lithofacies maps, various graphs, and other types of presentations. The database containing information on the geological reservoir characterization study and regional correlations will be available at the UGS's Leadville Limestone project Web site at the conclusion of the project.

Regional Stratigraphic Cross Sections

We are correlating major Paleozoic formations throughout the Paradox Basin from over 100 wells that penetrate the Leadville Limestone. These include formations of Pennsylvanian age (Paradox, Pinkerton Trail, and Molas), Mississippian age (Leadville Limestone), Devonian age (Ouray, Elbert, and Aneth), and Cambrian age (Lynch Dolomite, Bright Angel Shale, and Ignacio Quartzite). Formation tops are being entered into the INTEGRAL database. A grid of regional, stratigraphic, geophysical well-log cross sections, using the base of the Leadville as a datum, were produced tying in wells from producing fields to exploratory wells (figures 5 and 6). These cross sections show thickness relationships of important stratigraphic intervals, and will be combined during Budget Period II with facies types described from Leadville cores throughout the basin. This will provide a significant database for (1) locating potential exploration trends, (2) producing regional facies and isochore maps, (3) determining the major contacts, seals, barriers, and baffles (anhydrite, shale, and low-permeability carbonate) to fluid flow, and (4) identifying hydrocarbon migration pathways.

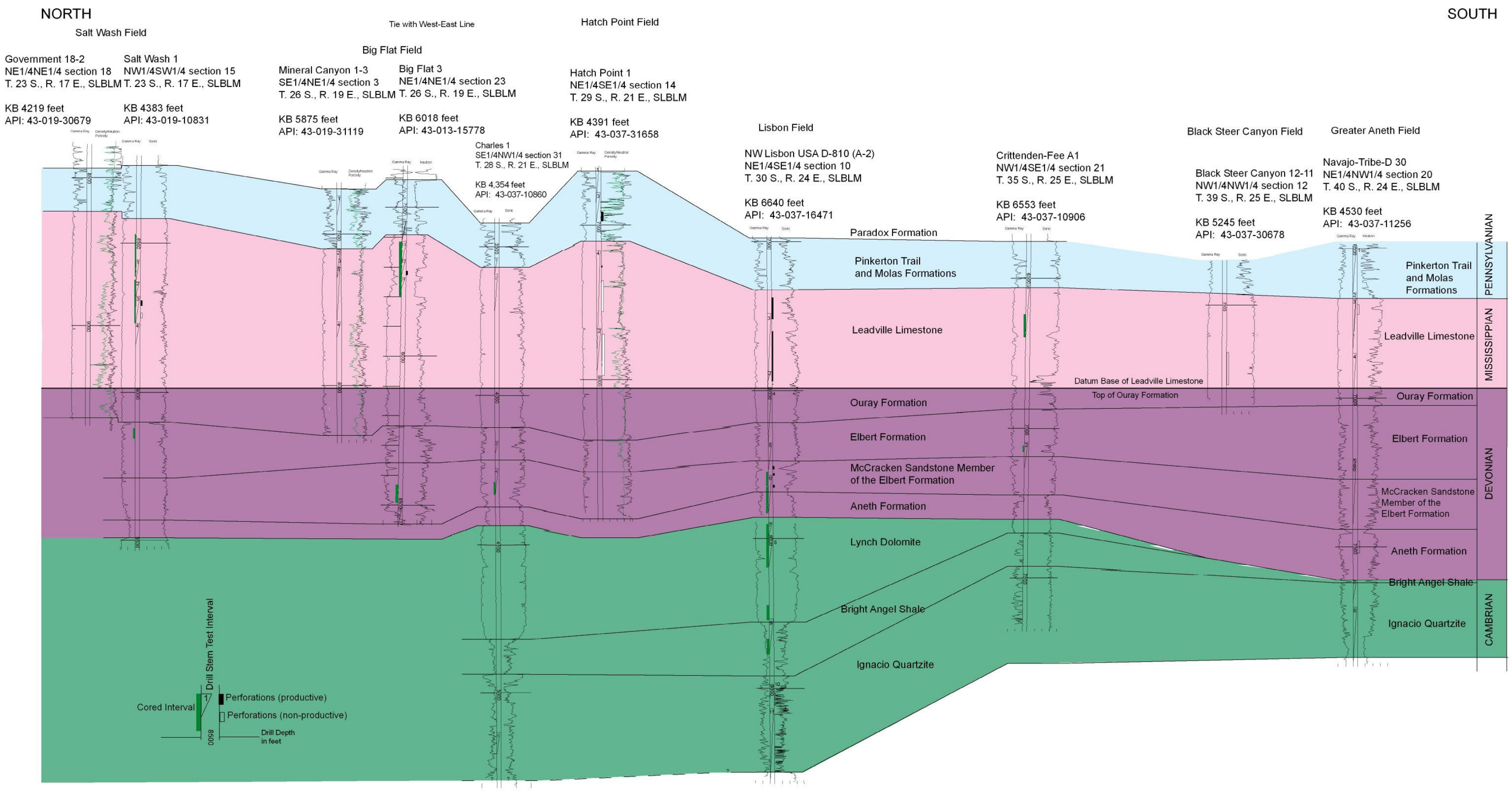


Figure 5. North-south stratigraphic cross section through the Utah portion of the Paradox Basin showing regional Paleozoic correlations.

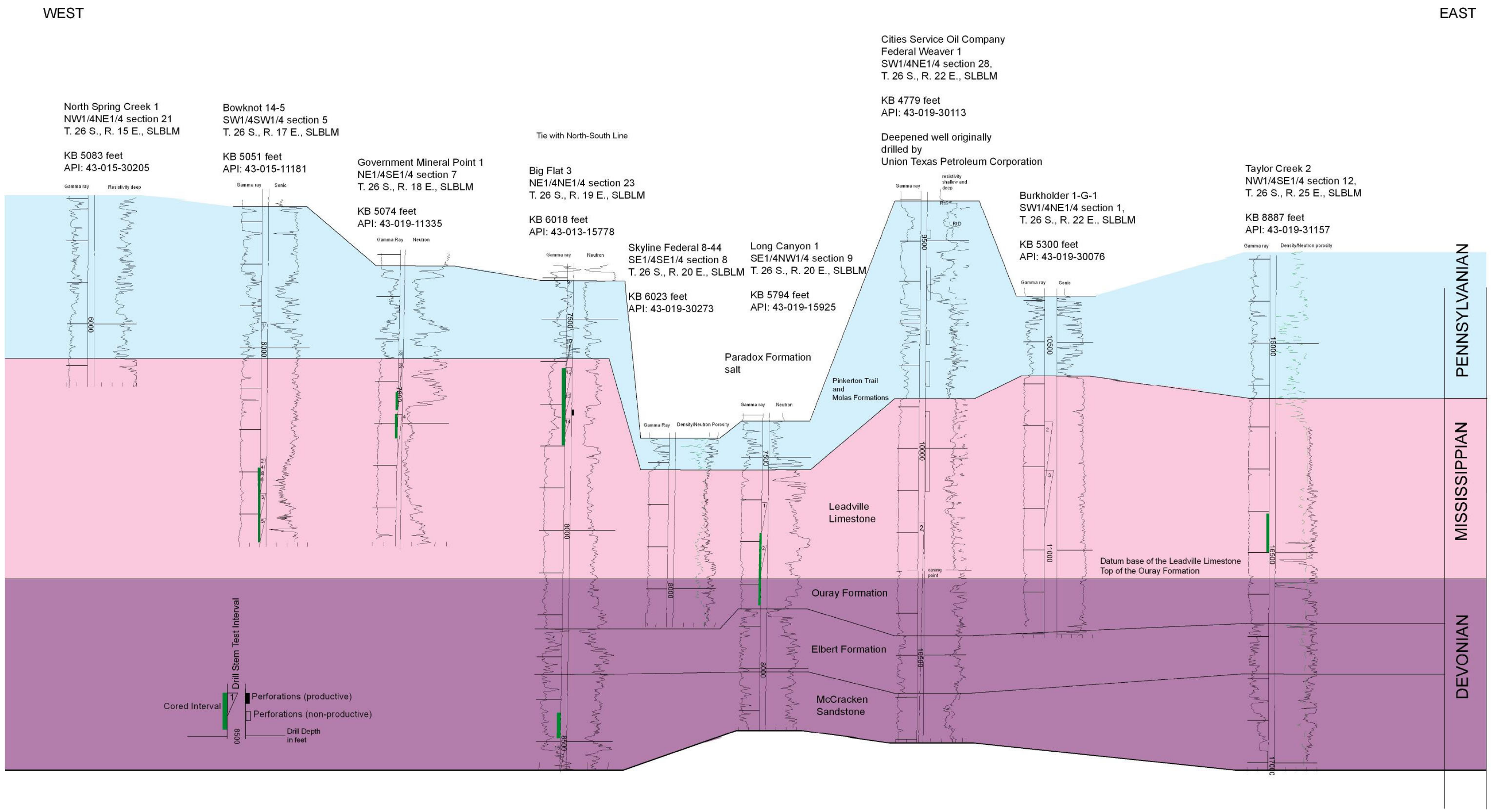


Figure 6. East-west stratigraphic cross section through the Utah portion of the Paradox Basin showing regional Paleozoic correlations.

LEADVILLE LIMESTONE RESERVOIR–
RESULTS AND DISCUSSION

General Leadville Characteristics

The Mississippian (late Kinderhookian through Osagean to early Meramecian time) Leadville Limestone is a shallow, open marine, carbonate-shelf deposit. The western part of the Paradox fold and fault belt includes a regional, reflux-dolomitized, interior bank facies containing Waulsortian mounds (Welsh and Bissell, 1979). During Late Mississippian time, the entire carbonate platform in southeastern Utah and southwestern Colorado was subjected to subaerial erosion resulting in formation of a lateritic regolith (Welsh and Bissell, 1979). This regolith and associated carbonate dissolution is an important factor in Leadville reservoir potential. The Leadville Limestone thins from more than 700 feet (230 m) in the northwest corner of the Paradox Basin to less than 200 feet (70 m) in the southeast corner (Morgan, 1993) (figure 3). Thinning is a result of both depositional onlap onto the Mississippian cratonic shelf and erosion. The Leadville is overlain by the Pennsylvanian Molas Formation and underlain by the Devonian Ouray Limestone (figure 2).

Periodic movement along northwest-trending faults affected deposition of the Leadville Limestone. Crinoid banks or mounds, the primary reservoir facies (figure 7), accumulated in shallow-water environments on upthrown fault blocks or other paleotopographic highs. In areas of greatest paleorelief, the Leadville is completely missing as a result of non-deposition or subsequent erosion (Baars, 1966).

Figure 7. Typical crinoidal and skeletal grainstone/packstone representing a high-energy, open-marine shoal environment of deposition for the Leadville Limestone; slabbed core from the Lisbon No. B-816 well, Lisbon field, San Juan County, Utah.

The Leadville Limestone is divided into two members separated by an intraformational discomformity (figure 8). The dolomitic lower member is composed of mudstone, wackestone, packstone, and grainstone deposited in shallow-marine, subtidal, supratidal, and intertidal environments (Fouret, 1996). Fossils include crinoids, fenestrate bryozoans, and brachiopods. Locally, mud-supported boundstone creates buildups or mud mounds, involving growth of algae, similar to Waulsortian facies (Wilson, 1975; Ahr, 1989; Fouret, 1996). The upper member is composed of mudstone, packstone, grainstones (limestone and dolomite), and terrigenous clastics also deposited in subtidal, supratidal, and intertidal environments (Fouret, 1996). Fossils include crinoids and rugose coral. Reservoir rocks are crinoid-bearing packstone (Baars, 1966).

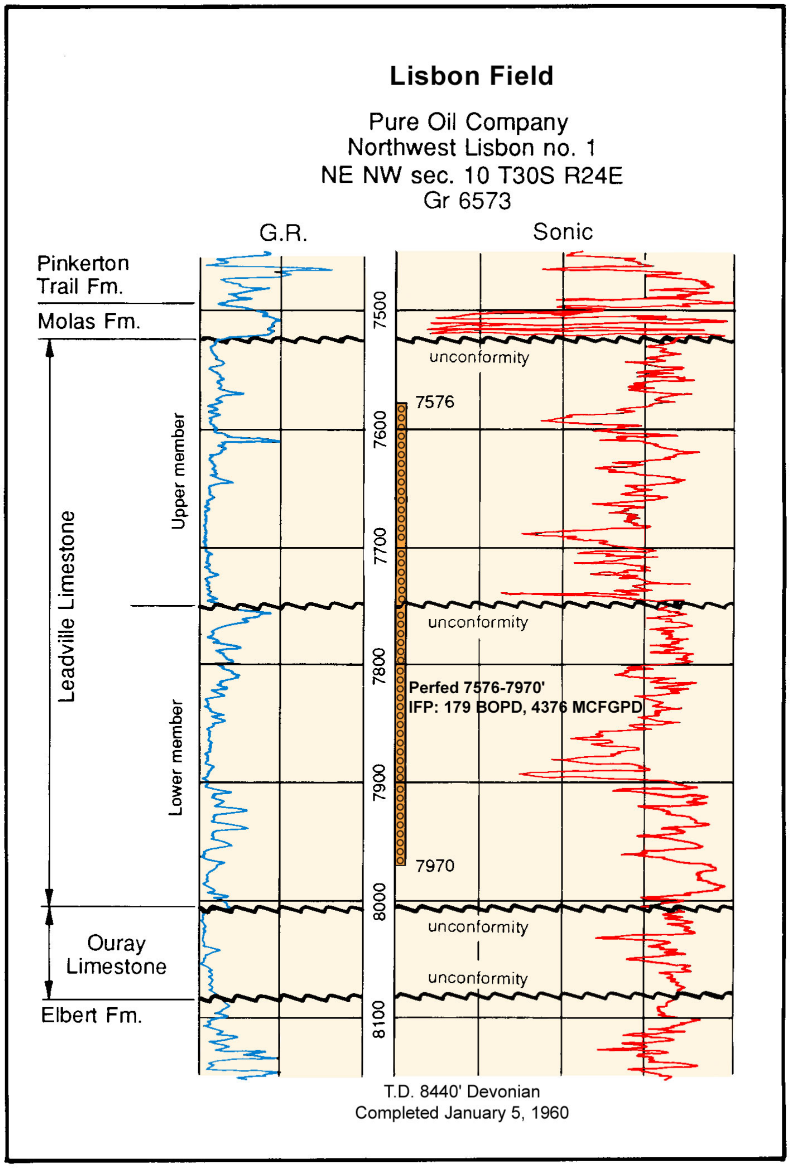


Figure 8. Typical gamma ray-sonic log of the Leadville Limestone, Lisbon field discovery well, San Juan County, Utah. See figures 1 and 3 for location of Lisbon field.

Intercrystalline porosity developed between dolomite rhombs (figure 9A), while vugs and moldic porosity formed by the dissolution of fossils (figure 9B). Reservoir porosity averages 6 to 8 percent, and permeability ranges from less than 1 to 1100 millidarcies (mD) (Smouse, 1993). Solution breccia and karstified surfaces are common, including possible local development of cavernous zones (Fouret, 1996). Reservoir quality is greatly improved by natural fracture systems associated with the Paradox fold and fault belt. The reservoir drive mechanisms are gas expansion, water drive, and, to a lesser degree, gravity drainage. Many Leadville reservoirs have a gas cap with an oil ring containing associated gas. Good pressure communication and efficient recoveries from the volumetric/pressure depletion fields are common.

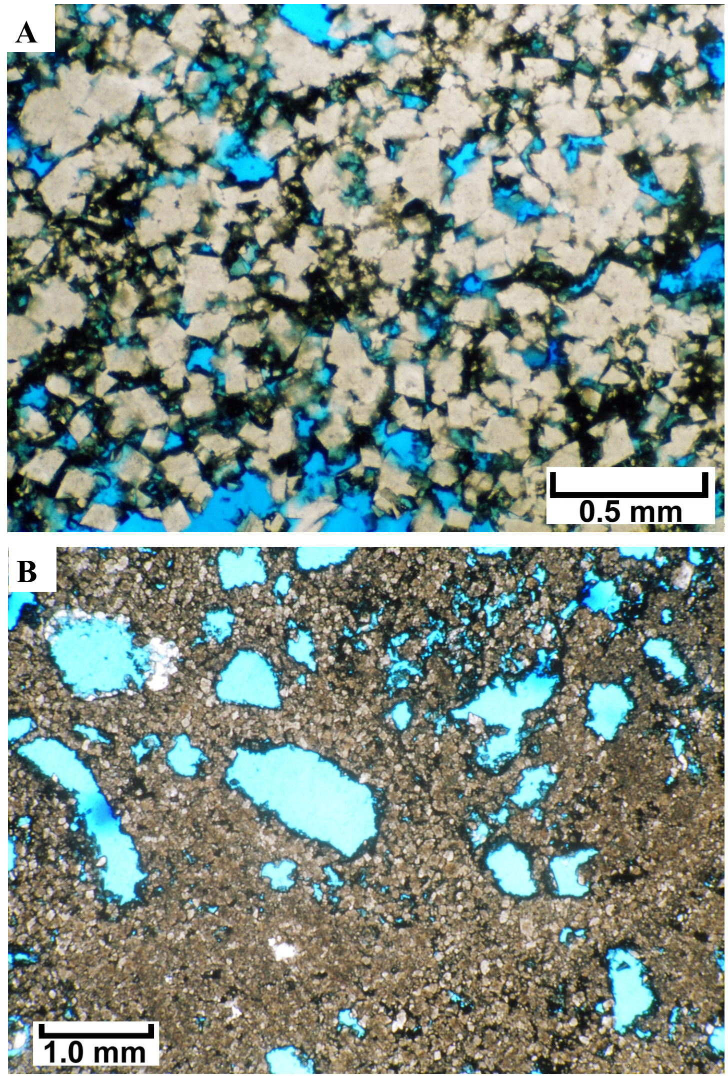


Figure 9. A - Photomicrograph (plane light) of intercrystalline porosity (in blue) in between coarse dolomite rhombs, with some bitumen plugging, in an original crinoidal grainstone/packstone. Lisbon No. D-816 well, 8435.8 feet (2571.1 m), porosity = 7.5 percent, permeability = 0.3 mD. B - Photomicrograph (plane light) of a crinoidal/peloidal wackestone showing moldic porosity (in blue), created from the dissolution of skeletal grains, within finely crystalline dolomite. Lisbon No. D-816 well, 8433 feet (2570 m), porosity = 2 percent, permeability < 7.5 mD.

In summary, three factors create reservoir heterogeneity within productive zones: (1) variations in carbonate fabrics and facies, (2) diagenesis (including karstification), and (3) fracturing. The extent of these factors and how they are combined affect the degree to which they create barriers to fluid flow.

Big Flat Field, Grand County, Utah

Big Flat field, Grand County, Utah, was the first Mississippian discovery in the Paradox Basin (figure 3). The trap is a north-south-trending anticline with 276 feet (84 m) of structural closure (figure 10) that produced from Leadville limestone and dolomite (Smith, 1978). The net reservoir thickness is 30 feet (10 m), which extends over a 480-acre (190 ha) area. Porosity ranges from 4 to 14 percent in vuggy and intercrystalline pore systems that are enhanced by vertical fractures. Permeability varies and is dependent, therefore, on the extent of fracture development. The drive mechanism is water drive with an inert gas cap and the initial water saturation was 30 to 50 percent (Smith, 1978). The field now produces oil from horizontal wells in the Cane Creek shale of the Pennsylvanian Paradox Formation, on a separate structure north of the original Leadville feature.

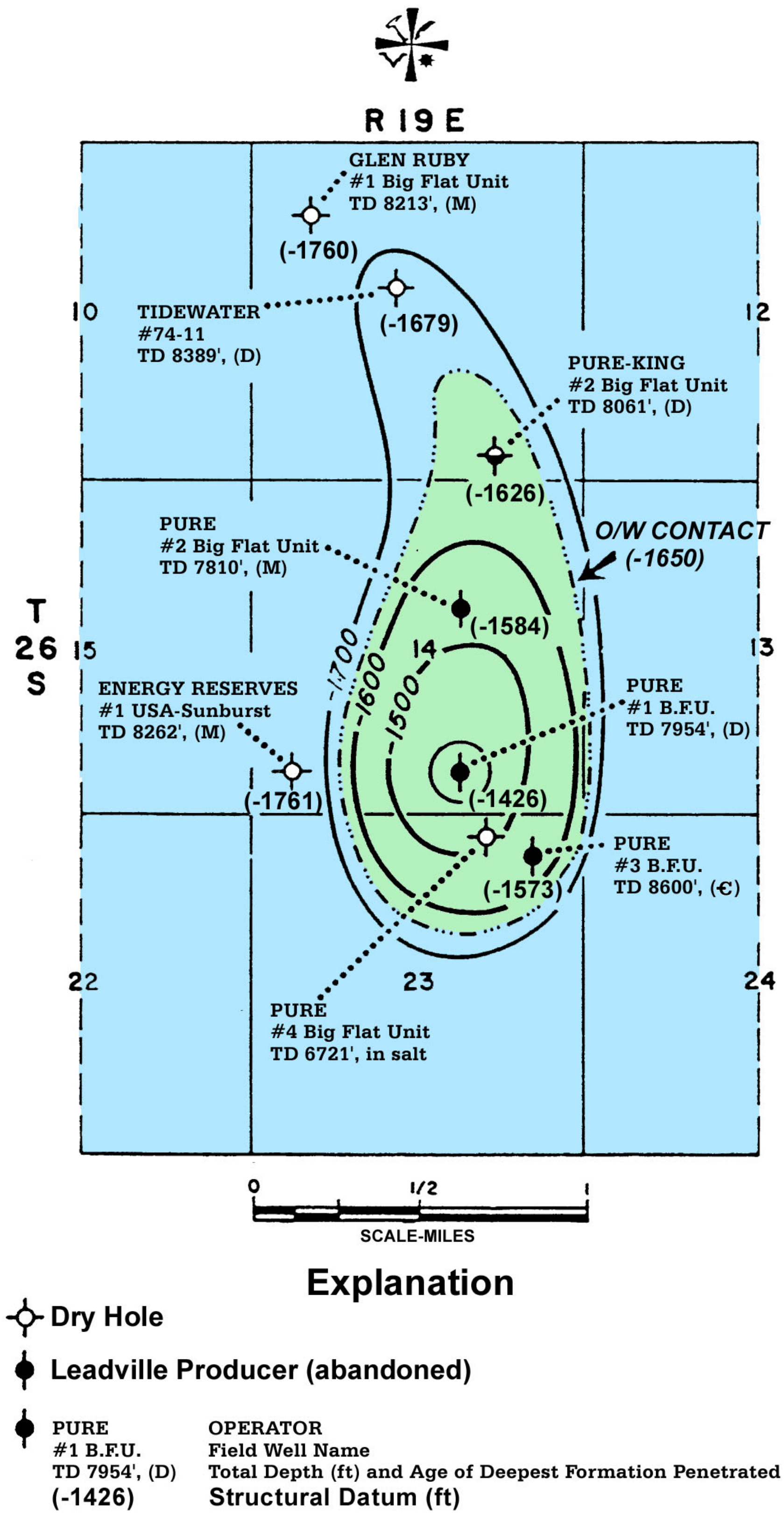
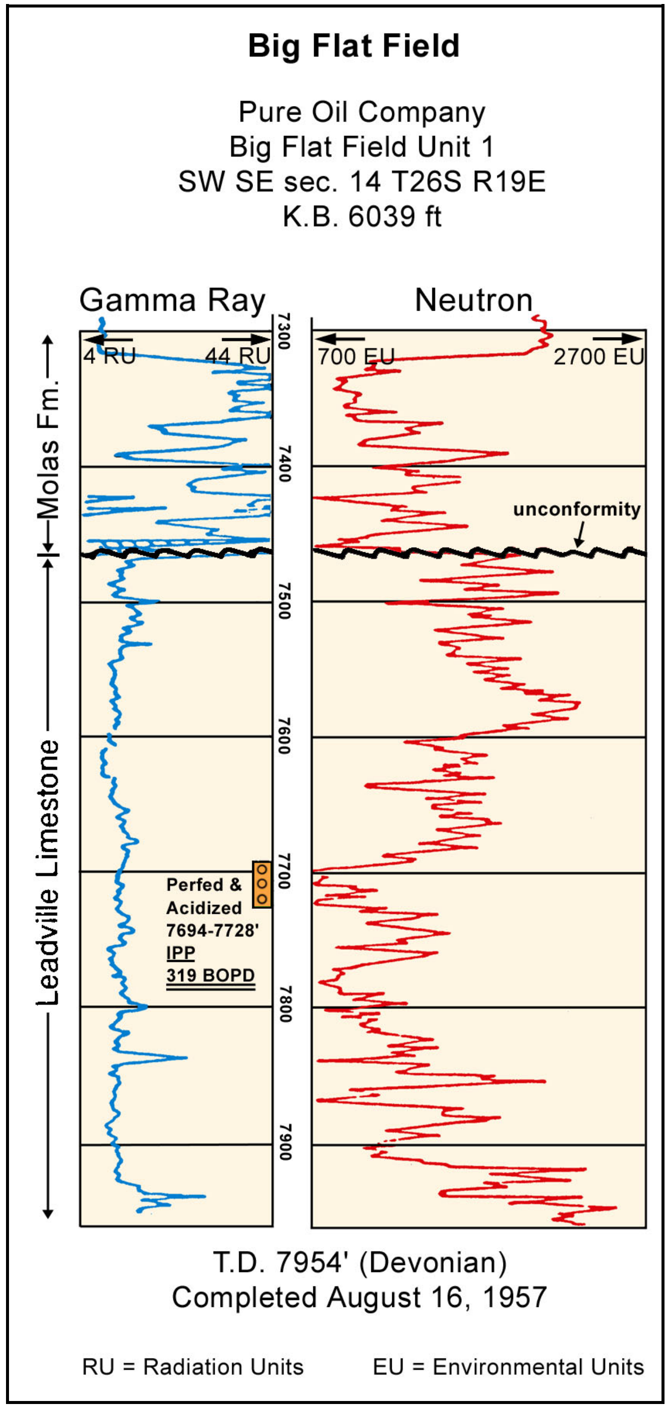


Figure 10. Top of structure of the Leadville Limestone, Big Flat field, Grand County, Utah (modified from Smith, 1978).

Big Flat field was discovered in 1957, with the completion of the Pure Oil Company No. 1 Big Flat Unit well (figures 10 and 11), SW1/4SE1/4 section 14, T. 26 S., R. 19 E., Salt Lake Base Line and Meridian (SLBL&M); initial flowing potential (IFP) was 319 bbls of oil per day (BOPD) (51 m^3/d). The original Leadville reservoir field pressure was 2450 pounds per square inch (psi) (16,900 kPa) (Smith, 1978). The Leadville reservoir was abandoned in 1968. Cumulative Leadville production was 83,469 bbls of oil (13,272 m^3), 52.4 billion cubic feet of gas (BCFG) (1.5 BCMG), and 41,950 bbls of water (6670 million m^3) from three wells (Stowe, 1972).

Figure 11. Original gamma ray-radioactivity log of the Leadville Limestone, Big Flat field discovery well, Grand County, Utah. See figures 1 and 3 for location of Big Flat field.



Lisbon Field, San Juan County, Utah

Lisbon field, San Juan County, Utah (figure 3) accounts for most of the Leadville oil production in the Paradox Basin. The trap is an elongate, asymmetric, northwest-trending anticline, with nearly 2000 feet (600 m) of structural closure and bounded on the northeast flank by a major, basement-involved normal fault with over 2500 feet (760 m) of displacement (Smith and Prather, 1981) (figure 12). Several minor, northeast-trending normal faults dissect the Leadville reservoir into segments. Producing units contain dolomitized crinoidal/skeletal grainstone (figure 7), packstone, and wackestone fabrics. Diagenesis includes fracturing, autobrecciation, karst development, hydrothermal (?) dolomite, and bitumen plugging. The net reservoir thickness is 225 feet (69 m) over a 5120-acre (2100 ha) area (Clark, 1978; Smouse, 1993). Porosity averages 6 percent in intercrystalline and moldic networks (figure 9) enhanced by fractures; permeability averages 22 mD. The drive mechanism is an expanding gas cap and gravity drainage; water saturation is 39 percent (Clark, 1978; Smouse, 1993).

Lisbon field was discovered in 1960 with the completion of the Pure Oil Company No. 1 NW Lisbon USA well, NE1/4NW1/4 section 10, T. 30 S., R. 24 E., SLBL&M (figures 8 and 12), with an IFP of 179 BOPD (28 m^3) and 4376 MCFGPD (124 MCMPD). The original reservoir field pressure was 2982 psi (20,560 kPa) (Clark, 1978). There are currently 23 producing (or shut-in wells), 10 abandoned producers, five injection wells (four gas injection wells and one water/gas injection well), and four dry holes in the field. Cumulative production as of March 31, 2004, was 51,087,114 bbls of oil (812,285 m^3), 765 BCFG (21.7 BCMG) (cycled gas), and 49,621,406 bbls of water (7,889,804 m^3) (Utah Division of Oil, Gas and Mining, 2004). Gas that was re-injected into the crest of the structure to control pressure decline is now being produced.

Recommended Reservoir Case Study: Lisbon Field, San Juan County, Utah

Reservoir characterization of the Leadville Limestone is not complete and little pertinent data is publicly available. There are few published core descriptions, permeability data, and diagenetic analyses. A case study of the Leadville reservoir at Lisbon field, where the UGS has a wealth of undescribed core and other raw data, will be conducted during the remaining portion of Budget Period I in order to understand the reservoir characteristics and facies that can be applied regionally. This case study will include the following work:

- Conventional core will be described (fabic, lithology, structures, fossils, and other characteristics) and digitally photographed. These descriptions will be augmented with available petrophysical data. Facies, visible diagenesis, porosity types, and reservoir trends will then be determined.

- Geophysical logs from Lisbon field wells with cores will be analyzed and compared to the conventional core descriptions and/or petrophysical properties from core plugs to create "type" logs matching the distribution of diagenetic processes, carbonate pore types, and permeability trends to log character. The logs will then be used to help determine the distribution of diagenetic processes, identify pore types, and map facies, to estimate these trends in wells where conventional cores were not taken in the field and Leadville Limestone play regionally.

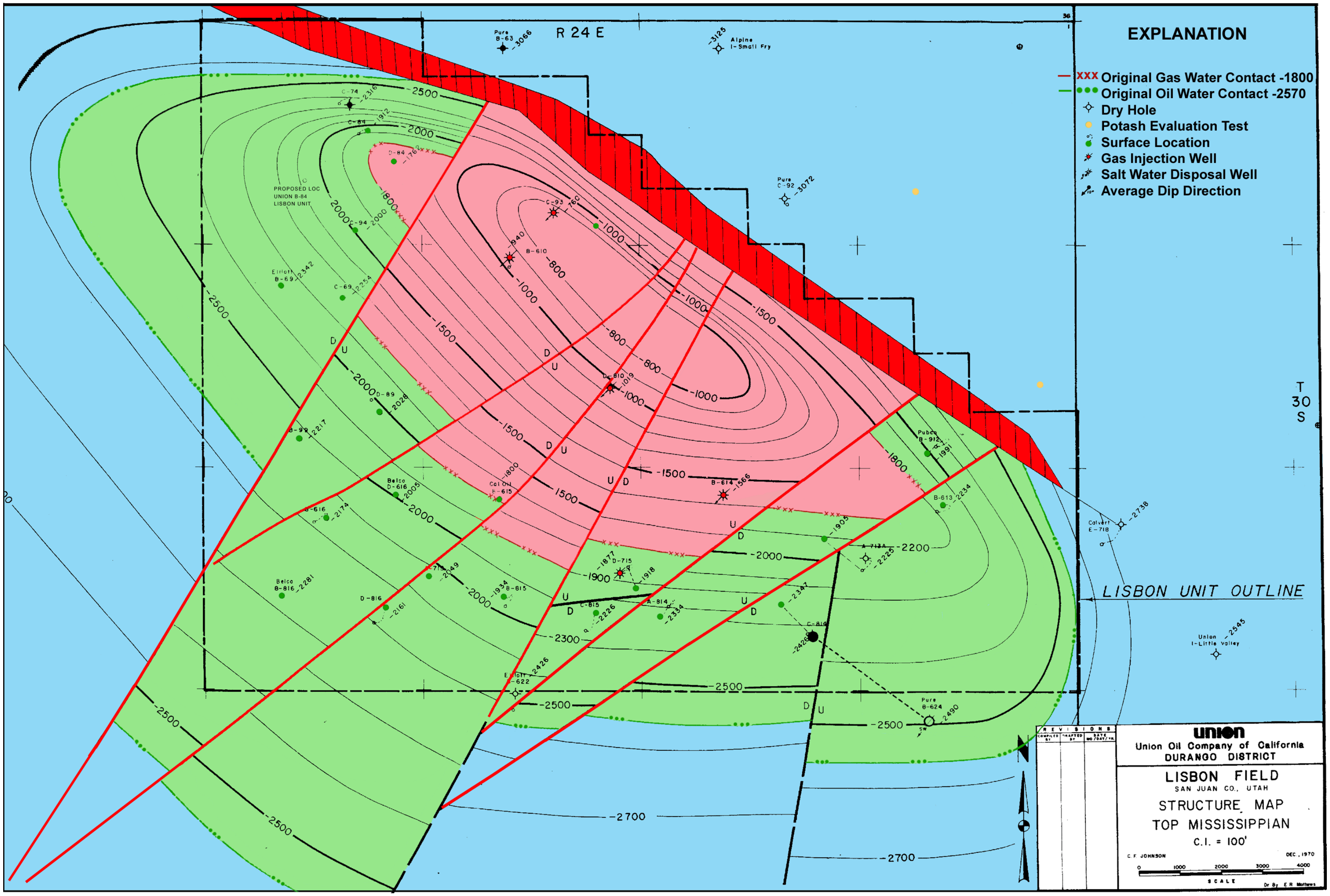


Figure 12. Top of structure of the Leadville Limestone, Lisbon field, San Juan County, Utah (modified from C.F. Johnson, Union Oil Company of California files, 1970; courtesy of Tom Brown, Inc.).

- Diagenesis and pore types that are prevalent for Lisbon field will be catalogued and the diagenetic history determined. Emphasis will include petrographic (thin section) and geochemical analysis of selected representative reservoir and non-reservoir lithologies. Typical techniques that will be employed involve epi-fluorescence and cathodoluminescence petrography for the sequence of diagenesis, stable carbon and oxygen isotope analysis of diagenetic components such as cementing minerals and different generations of dolomites (hydrothermal dolomite for example), strontium isotopes for tracing the origin of fluids responsible for different diagenetic events, fluid inclusion analysis to determine temperature of cement formation, and scanning electron microscope (SEM) analysis of various dolomites and pores to determine reservoir quality of the dolomites as a function of diagenetic history.

- The principal Leadville facies will be determined and various maps will be constructed, such as (1) top of structure, (2) gross carbonate thickness and net pay thickness, (3) porosity, (4) permeability, (5) lithology, and (6) microfacies.

Surface Geochemical Surveys and Epi-Fluorescence

Surface geochemical surveys have recently been shown in the Michigan and Williston Basins to help identify areas of poorly drained or by-passed oil in pinnacle reef fields (Wood and others, 2001, 2002). Surface geochemical surveys will be conducted during Budget Period II of the Mississippian Leadville Limestone project at Big Flat and Lisbon fields. These fields are ideal because proven hydrocarbons underlie the areas, and the fields are easily accessible. They also will provide interesting and useful comparisons because of their differences. The Leadville-producing area of Big Flat field has been abandoned for 36 years and produced a relatively small amount of hydrocarbons. Big Flat is underlain by relatively flat-lying, unfaulted, Jurassic strata covered by Quaternary alluvium. Lisbon field is the largest Leadville oil producer and is currently producing over 3600 bbls (570 m^3) per month. The surface geology is similar to the structure of the field – a major northwest-southeast-trending anticline (tens of miles in length) along the Lisbon fault, which displaces the Pennsylvanian Honaker Trail Formation against Cretaceous strata. The Leadville reservoirs in Lisbon and Big Flat fields are separated from upper Paleozoic and Mesozoic strata by cyclic evaporites in the Pennsylvanian Paradox Formation.

In the Leadville project, geochemical surveys will consist of one or more combinations of the following techniques: microbial, soil gas, iodine, and trace elements. The microbial surveys are based on the concept that the type of microbes living in the soil, vary according to their food source. Some microbes thrive on light hydrocarbons (methane through butane). Samples are collected 8 inches (20 cm) below the ground surface, then cultured in a laboratory and the microbe population counted. If certain microbes are present, then it is assumed that the corresponding gases that they consume are present; ethane, propane, and butane in soil are considered to have originated from oil and gas accumulations. Thus, the presence of microbes that feed on these gases is an indication that hydrocarbons have migrated from depth. Absorbed soil gas is detected using gas chromatography-mass spectrometry and produces similar results as the microbial analysis. Iodine and trace elements are also detected using gas chromatography-mass spectrometry.

Sampling grids will extend beyond the proven limits of the Big Flat and Lisbon fields to establish background readings. Sample locations, as many as 1000 for each field, will be pinpointed using global positioning satellite (GPS) units. Sampling techniques may require some adjustments depending on soil or the lack of it (rock outcrop). Each site will be sampled at different times of the year to identify any weather effects such as atmospheric pressure or soil moisture conditions. Evidence of surface alteration that could be attributed to hydrocarbon seepage and fracturing will also be noted. Sample results will be plotted and contoured to identify any surficial geochemical anomalies.

Another new technique to be employed will be to characterize Leadville oil from Lisbon field using low-cost epi-fluorescence techniques. This analysis will be compared to epi-fluorescence in the cores and cuttings from the field, thus establishing a Leadville epi-fluorescence standard. The standard can then be used to identify where Leadville oil has migrated by comparing it to the cuttings and core from regional wells. The net product will be a regional Leadville quality of show map designed to identify Leadville oil provinces and migration patterns (no hydrocarbons, hydrocarbons passed through, hydrocarbons present but not mobile, hydrocarbons mobile). The map will incorporate data and interpretations from regional, middle Paleozoic, hydrodynamic-pressure-regime analysis.

Surface geochemical surveys represent a low-cost alternative to 3D seismic acquisition. Sample analyses using some of these techniques cost as low as $20 per sample and anomalies are easy to identify. Epi-fluorescence of well cuttings is equally inexpensive, fast, and conclusive.

TECHNOLOGY TRANSFER

The UGS is the Principal Investigator and prime contractor for the Leadville Limestone project. All maps, cross sections, lab analyses, reports, databases, and other deliverables produced for the project will be published in interactive, menu-driven digital (Web-based and compact disc) and hard-copy formats by the UGS for presentation to the petroleum industry. Syntheses and highlights will be submitted to refereed journals, as appropriate, such as the *American Association of Petroleum Geologists (AAPG) Bulletin* and *Journal of Petroleum Technology*, and to trade publications such as the *Oil and Gas Journal*.

The technology-transfer plan includes the formation of a Technical Advisory Board and a Stake Holders Board. These boards meet annually with the project technical team members. The Technical Advisory Board advises the technical team on the direction of study, reviews technical progress, recommends changes and additions to the study, and provides data. The Technical Advisory Board is composed of Leadville field operators and those who are actively exploring for Leadville hydrocarbons in Utah and Colorado. This board ensures direct communication of the study methods and results to the operators. The Stake Holders Board is composed of groups that have a financial interest in the study area including representatives from the State of Utah (School and Institutional Trust Lands Administration, and Utah Division of Oil, Gas and Mining) and the Federal Government (Bureau of Land Management). The members of the Technical Advisory and Stake Holders Boards receive all semi-annual technical reports, copies of all publications, and other material resulting from the study. Board members will also provide field and reservoir data.

An abstract describing the Leadville Limestone play and reservoir characteristics was accepted by the American Association of Petroleum Geologists, for presentation at the 2004 Rocky Mountain Section Meeting in Denver, Colorado.

Utah Geological Survey *Survey Notes* and Web Site

The UGS publication *Survey Notes* provides non-technical information on contemporary geologic topics, issues, events, and ongoing UGS projects to Utah's geologic community, educators, state and local officials and other decision-makers, and the public. *Survey Notes* is published three times yearly. Single copies are distributed free of charge and reproduction (with recognition of source) is encouraged. The UGS maintains a Web site on the Internet, http://geology.utah.gov. The UGS site includes a page under the heading *Utah Geology/Oil, Coal, and Energy*, which describes the UGS/DOE cooperative studies (Leadville Limestone, PUMPII, Paradox Basin [two projects evaluating the Pennsylvanian Paradox Formation], Ferron Sandstone, Bluebell field, Green River Formation), and has a link to the DOE Web site. Each UGS/DOE cooperative study also has its own separate page on the UGS Web site. The Leadville Limestone project page (figure 13), http://geology.utah.gov/emp/leadville/index.htm, contains (1) a project location map, (2) a description of the project, (3) a reference list of all publications that are a direct result of the project, (4) poster presentations, and (5) semi-annual technical progress reports.

Project Publications

The following publications promoted and described project work, goals, and objectives of the Leadville Limestone study:

Chidsey, T.C., Jr., 2004, The UGS awarded DOE grant to study the Mississippian Leadville Limestone oil exploration play in Utah and Colorado: Utah Geological Survey, Survey Notes, v. 36, no. 1, p. 5-6.

PI/Dwights Plus Drilling Wire, 2004, UGS carrying out study of Leadville in Paradox Basin: PI/Dwights Rocky Mountain Region, Four Corners Edition, Section I, February, p 3.

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

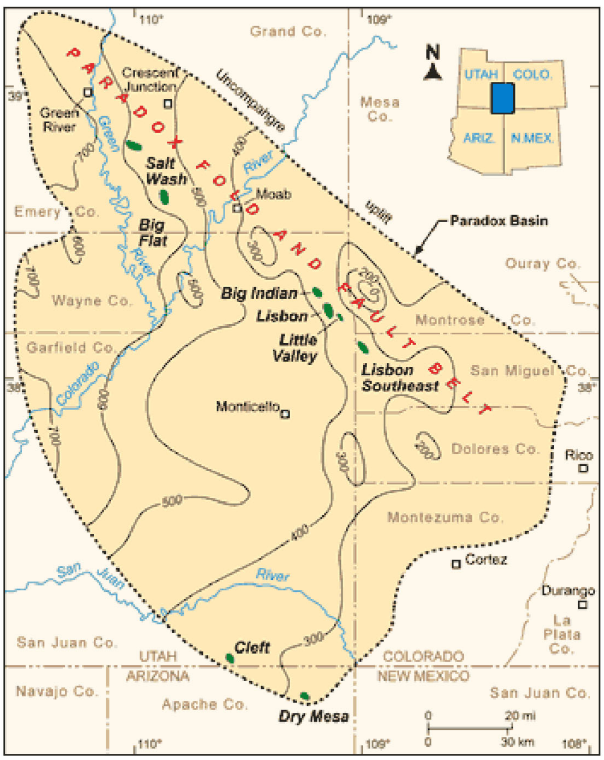
The Mississippian Leadville Limestone is a shallow, open-marine, carbonate-shelf deposit. The Leadville has produced over 53 million barrels (8.4 million m^3) of oil from six fields in the Paradox fold and fault belt of the Paradox Basin, Utah and Colorado. Most Leadville oil and gas production is from basement-involved structural traps. All of these fields are currently operated by small, independent producers. This environmentally sensitive, 7500-square-mile (19,400 km^2) area is relatively unexplored. Only independent producers continue to hunt for Leadville oil targets in the region.

Leadville Limestone Exploration Play

The Mississippian Leadville Limestone Exploration Play, Utah and Colorado: Exploration Techniques and Studies for Independents

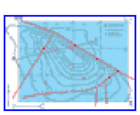
Reports

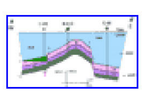
- Abstracts, Public & Technical (pdf)
- Statement of Work (pdf)



Fields of Paradox Basin.
modified from Parker and Roberts, 1963

Case-Study Field: Lisbon, San Juan Co., Utah


Structure contour***

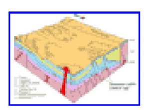

Schematic cross section***

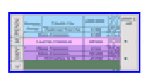
Outcrop reservoir analogs: Mississippian Redwall Limestone, Grand Canyon

Other Images:

Click on images to enlarge.


Typical Leadville core, Lisbon field, San Juan Co., Utah


Block diagram: Leadville trapping mechanisms*


Paradox Basin stratigraphic section**

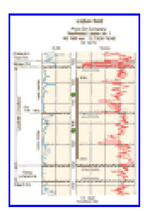

Leadville Limestone type log

Figure 13. The Leadville Limestone project page, http://geology.utah.gov/emp/leadville/index.htm, from the UGS Web site.

We are correlating major Paleozoic formations throughout the Paradox Basin from the wells that penetrate the Leadville Limestone. A grid of regional stratigraphic cross sections tying in wells from producing fields to exploratory wells shows thickness relationships of important stratigraphic intervals and will be combined with core-derived Leadville facies types. This will provide a significant database to determine (1) potential exploration trends, (2) regional facies, (3) seals, barriers, and baffles to fluid flow, and (4) hydrocarbon migration pathways.

Reservoir characterization of the Leadville Limestone is not complete and little pertinent information (core descriptions, permeability data, and diagenetic analysis) has been published. The UGS recommends, as part of the project, conducting a case study of the Leadville reservoir at Lisbon field, Utah, where there is a wealth of undescribed core and other raw data at the Survey's Core Research Center. The reservoir characteristics, particularly diagenetic overprinting and history, and Leadville facies can be applied regionally to other fields and exploration trends.

Surface geochemical surveys have proved to help identify areas of poorly drained or by-passed oil in other basins. We recommend that surface geochemical surveys be conducted, as part of the project (Phase II), at Big Flat and Lisbon fields, Utah. These fields are ideal because proven hydrocarbons underlie the areas, and the fields are easily accessible. The Leadville producing area of Big Flat field is abandoned and produced a relatively small amount of hydrocarbons. The surface geology at Big Flat field is flat-lying, unfaulted, Jurassic strata covered by Quaternary alluvium. Lisbon field is the largest Leadville producer and is still actively producing oil and gas. The surface geology at Lisbon field consists of a major anticline along a large normal fault. Proving the success of geochemical surveys at Big Flat or Lisbon fields will allow independent operators to reduce risks and minimize impact on environmentally sensitive areas while exploring for Leadville targets.

ACKNOWLEDGMENTS

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James Parker of the Utah Geological Survey (UGS) drafted figures and Cheryl Gustin, UGS, formatted the manuscript. This report was reviewed by David Tabet and Michael Hylland of the UGS.

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